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IN REPLY REFER TO:

Attorney Docket No. 83154
Date: 27 August 2002

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Serial Number 10/161,993
Filing Date 31 May 2002
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20020903076

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FILIGREE ELECTRODE PATTERN APPARATUS FOR
STEERING PARAMETRIC MODE ACOUSTIC BEAMS

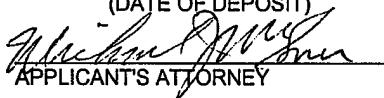
TO ALL WHOM IT MAY CONCERN:

BE IT KNOWN THAT (1) KIM C. BENJAMIN, (2) STEVE E. FORSYTHE, employees of the United States Government, and (3) WILLIAM L. KONRAD citizens of the United States of America, and residents of (1) Portsmouth, County of Newport, State of Rhode Island, (2) Portsmouth, County of Newport, State of Rhode Island and (3) Niantic, County of New London, State of Connecticut, have invented certain new and useful improvements entitled as set forth above of which the following is a specification.

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(DATE OF DEPOSIT)


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5-31-02
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23523

PATENT TRADEMARK OFFICE

1 Attorney's Docket No. 83154

2

3 FILIGREE ELECTRODE PATTERN APPARATUS FOR
4 STEERING PARAMETRIC MODE ACOUSTIC BEAMS

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6 STATEMENT OF GOVERNMENT INTEREST

7 The invention described herein may be manufactured and used
8 by or for the Government of the United States of America for
9 governmental purposes without the payment of any royalties
10 thereon or therefor.

11

12 CROSS REFERENCE TO OTHER PATENT APPLICATIONS

13 Not applicable.

14

15 BACKGROUND OF THE INVENTION

16 (1) Field of the Invention

17 The present invention relates to a transducer for steering
18 parametric mode acoustic beams. More specifically, the present
19 invention relates to an apparatus comprised of a plurality of
20 elements apodized from a conductive material and arranged over a
21 piezoelectric continuum surface to direct an acoustic beam at a
22 desired frequency and steering angle.

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1 (2) Description of Prior Art

2 It is practiced in the art to dispose four electrically
3 phased signals (0, 90, 180, 270 degrees) through an array of
4 piezoelectric elements over a piezoelectric continuum surface to
5 direct an acoustic beam at a desired frequency and steering
6 angle such as described in U.S. Patent 6,108,275 to Hughes et
7 al. This conventional, or non-parametric, configuration
8 operates in the linear mode. In a linear mode, changing the
9 frequency results in a change to the steering angle.

10 In general, if an array contains N-by-N elements, the
11 number of independent control points required for broadband beam
12 steering equally in two dimensions is N^2 . As used herein, "beam
13 steering" refers to directing acoustic energy from a moving
14 surface in a desired direction, usually by varying the amplitude
15 and phase of the individual parts of the surface in a systematic
16 manner over the surface. Beam "steering angle" is the angle at
17 which acoustic energy is directed relative to the face of the
18 transducer. Because the number of control points increases as
19 the square of piezoelectric elements in any of two orthogonal
20 directions comprising the array, the complexities of fabrication
21 and control of the array similarly increase with the addition of
22 elements. Because conventional, linear mode, low frequency
23 sources require very large radiating apertures to form
24 directional acoustic beams, they often require a large number of

elements and the attendant cost and complexity that goes with them.

3 What is therefore needed is an apparatus for directing an
4 acoustic beam comprised of piezoelectric elements that has a
5 relatively small radiating aperture, can be easily and
6 affordably fabricated, and which requires few control points to
7 operate an array of piezoelectric elements.

SUMMARY OF THE INVENTION

Accordingly, it is an object of the present invention to provide a transducer apparatus for steering wideband parametric mode acoustic beams.

13 In accordance with the present invention, a piezoelectric
14 embedded monolithic active surface for transmitting a directed
15 acoustic beam comprises a monolithic active surface, a plurality
16 of piezoelectric elements formed on said surface by the
17 apodization of a continuous conductor forming an array of
18 electrodes comprising, a plurality of coupled frequency pairs
19 comprising, a first primary frequency row extending in a
20 frequency steered direction the first primary frequency row
21 comprising means for accepting a first primary frequency signal,
22 and a second primary frequency row extending in the frequency
23 steered direction and located adjacent to the first primary
24 frequency row the second primary frequency row comprising means

1 for accepting a second primary frequency signal, wherein the
2 plurality of coupled frequency pairs repeat in a delay-steered
3 direction and wherein each of the coupled frequency pairs
4 comprises a means for accepting a time delayed copy of the first
5 and second primary frequency signals.

6

7 BRIEF DESCRIPTION OF THE DRAWINGS

8 FIG. 1 A perspective view of the monolithic active surface
9 of the present invention;

10 FIG. 2 A diagram of the filigree pattern of the present
11 invention; and

12 FIG. 3 A diagram of a parametric mode transducer and
13 directed acoustic beam of the present invention.

14

15

16 DESCRIPTION OF THE PREFERRED EMBODIMENT

17 In contrast to the linear case described above, where
18 changing the frequency must result in the change of steering
19 angle, steering of the acoustic beam along one axis is achieved
20 in the present invention by varying the frequencies of the two
21 primary drive signals independently. This allows the parametric
22 mode difference frequency to be varied while maintaining a fixed
23 arbitrary pointing angle. As used herein, "parametric mode"
24 refers to a technique for generating an acoustic signal with low

1 frequency by the nonlinear interaction over a finite region of
2 two high-intensity, high-frequency signals, or primary frequency
3 signals. The frequency of the low-frequency signal is equal to
4 the difference of the primary frequency signals. This
5 difference is commonly referred to as the "difference
6 frequency". The use and advantage of parametric mode is that
7 the beam width of the difference frequency signal can be made
8 small using a device that is physically small. This allows the
9 difference frequency to vary while retaining a constant beam
10 angle, therefore enabling broadband signals like FM chirps to be
11 conveyed with a narrow beamwidth while retaining control of the
12 steering angle.

13 As used herein, "beam width" refers to a measure of the
14 narrowness of an acoustic beam. Usually expressed in degrees,
15 indicating how many degrees wide the cone of greatest intensity
16 is. Narrow beam width is in general desirable since it means
17 that available acoustic energy is focused in one direction,
18 rather than dissipated in all directions (e.g., a flashlight vs.
19 a simple bulb with the same wattage).

20 In addition, the present invention teaches beam steering in
21 two orthogonal directions, allowing a full two-dimensional
22 raster scanning capability. This is done by combining the
23 filigree apodization-based steering in one direction described
24 more fully below with conventional time delay beam steering in

1 the orthogonal direction. The total complexity of drive
2 electronics is no more than that required to steer in one
3 direction with the addition of conventional time delay
4 techniques.

5 In this way, broadband signals like FM, or phase coded,
6 chirps may be generated over a broad range of difference
7 frequencies and directed to bearing angles of interest. As used
8 herein, "FM chirps" refer to sonar signals that start at a low
9 frequency and increases in frequency at later time. Bird sounds
10 are often chirps with varying frequency, hence the name.

11 The enabling mechanism of the subject invention is an
12 intricate electrode pattern, or filigree, that is illustrated in
13 FIG. 1. The electrode pattern forms an array of piezoelectric
14 elements 2 connected as described more fully below by connecting
15 wires 3. The piezoelectric elements 2 are mounted on the
16 surface of a monolithic active surface 1. In a preferred
17 embodiment, monolithic active surface 1 is fabricated from a 1-3
18 piezoelectric composite panel. The use of 1-3 piezoelectric
19 composite material possesses an inherently high thickness mode
20 coupling relative to lateral mode coupling. "Thickness mode",
21 and "lateral mode" refer to the ways in which a thin plate of
22 piezoelectric material responds to a driving voltage. Thickness
23 mode is the vibration in the direction perpendicular to the
24 plate. This is desirable, since it causes sound to be radiated

1 into the surrounding water. Lateral mode is the vibration along
2 the surface of the plate and is undesirable since it does not
3 reliably radiate sound, but instead causes unpredictable motion
4 (and resonances) of the plate.

5 In addition, due to its availability in large sheets, 1-3
6 piezoelectric composite material provides a cost effective means
7 of obtaining a continuous and homogeneous active layer several
8 wavelengths in aperture. However, the present invention is
9 broadly drawn to any active surface 1, including, but not
10 limited to, Polyvinylidene Fluoride (PVDF) sheets.

11 The piezoelectric elements described more fully below, are
12 arranged upon monolithic active surface 1 with reference to two
13 orthogonal axes oriented in a frequency steered direction 11 and
14 a delay steered direction 13.

15 Piezoelectric elements are generally arranged to form a
16 plurality of coupled frequency pairs of primary frequency rows
17 15,17 extending in frequency steered direction 11 and replicated
18 in delay steered direction 13. Each first primary frequency
19 row 15 is immediately adjacent to its corresponding second
20 primary frequency row 17 forming a coupled frequency pair 41.

21 In addition, a plurality of coupled frequency pairs 41 are
22 repeated in the delay steered direction 13 each pair adjacent to
23 at least one other.

1 With reference to FIG. 3, there is illustrated a diagram of
2 the monolithic active surface 1 shown in cross section
3 perpendicular to delay steered direction 13. As illustrated,
4 the transducer comprised of monolithic active surface 1 emits an
5 acoustic beam 12 at angle theta relative to the surface of the
6 monolithic active surface 1.

7 With reference to FIG. 2 there is illustrated in detail the
8 arrangement of the piezoelectric elements forming both first
9 primary frequency row 15 and second primary frequency row 17.
10 The precise location of each piezoelectric element in each
11 primary frequency row 15,17 is defined as described more fully
12 below by choosing a common steering angle theta and a primary
13 frequency for each primary frequency row 15,17. Once the
14 steering angle theta and a primary frequency is selected, one
15 can compute the required spacing for the piezoelectric
16 components comprising each primary frequency row 15,17. As a
17 result, each primary frequency row 15,17 differs from the other
18 in only two ways. First, each primary frequency row 15,17
19 receives as an input a different primary frequency signal and,
20 second, the spacing of the piezoelectric elements forming each
21 primary frequency row 15,17 differs. Therefore, while there is
22 herein described the layout of first primary frequency row 15,
23 the same methodology by which first primary frequency row 15 is

1 constructed is applied to construct second primary frequency row
2 17.

3 Primary frequency row 15 is divided into two rows: real
4 frequency row 27 and imaginary frequency row 29. Real frequency
5 row 27 is comprised of alternating R+ piezoelectric elements 19
6 and R- piezoelectric elements 21. All of the R+ piezoelectric
7 elements 19 are connected by the same wire 3 so as to receive a
8 first primary frequency signal. Likewise, all of the R-
9 piezoelectric elements 21 are connected by the same wire 3 so as
10 to receive a first primary frequency 180° shifted signal
11 comprised of the first primary frequency signal shifted by 180°.

12 Similarly, imaginary frequency row 29 is comprised of
13 alternating I+ piezoelectric elements 25 and I- piezoelectric
14 elements 23. All of the I+ piezoelectric elements 19 are
15 connected by the same wire 3 so as to receive a first primary
16 frequency 90° shifted signal comprised of the first primary
17 frequency signal shifted by 90°. Likewise, all of the I-
18 piezoelectric elements 23 are connected by the same wire 3 so as
19 to receive a first primary frequency 270° shifted signal
20 comprised of the first primary frequency signal shifted by 270°.

21 Note that the shape of each repeating piezoelectric element
22 forms a quadrant of a sinusoidal wave function. The
23 configuration of each piezoelectric element according to such a

1 shape gives rise to the following property. Consider an
2 arbitrary slice 4 drawn to span a single primary frequency row
3 15 and located an arbitrary distance x_0 from the left edge of
4 primary frequency row 15. A portion of slice 4 extends through
5 the area formed from a R- piezoelectric elements 21 as well as
6 the area formed from an I+ piezoelectric element 23. As
7 illustrated, the portion of slice 4 extending through I+
8 piezoelectric element 23 is shorter in length than the portion
9 of slice 4 extending through R- piezoelectric element 21. As x_0
10 is increased and slice 4 moves across first primary frequency
11 row 15, the proportions of slice 4 extending through R-
12 piezoelectric elements 21, R+ piezoelectric elements 19, I+
13 piezoelectric elements 25, and I- piezoelectric elements 23
14 continually change.

15 Specifically, the proportions of the active regions
16 comprised of the piezoelectric elements 19,21,23, and 25 along
17 the frequency steered direction 11 intersecting a slice 4 moved
18 in frequency steered direction 11, are proportional to the
19 positive and negative real and imaginary parts of the complex
20 surface velocity required to steer each primary beam in the x
21 direction as described more fully below. Real and imaginary
22 parts refer to the standard mathematical description of the
23 relative amplitudes of and phases of sinusoids. By convention,

1 cos(theta) corresponds to a real part=1 and imaginary part 0,
2 sin(theta) has real part 0, imaginary part 1, etc.
3 As illustrated in FIG. 2, multiple copies of the electrode
4 patterns forming primary frequency rows 15,17 are laid down in
5 the delay-steered direction 13 forming coupled frequency pairs
6 41. Each copy of primary frequency rows 15,17 is configured to
7 receive the primary frequency signals corresponding to the
8 inputs to each of original primary frequency rows 15,17 delayed
9 by a predetermined time delay. The time delay may be
10 implemented using any means of delaying an electronic signal
11 including, but not limited to, analog delay lines, digital delay
12 lines, and Charge Coupled Delay-lines CCDs. As, a result, the
13 primary acoustic beam signals created by the activation of the
14 monolithic active surface 1 by inputting a first and second
15 primary frequency signal as well as time delayed versions of the
16 first and second primary frequency signals can be steered in two
17 orthogonal directions. The directions of the two primary beams
18 (and thus of the parametric difference beam) are controlled by
19 simultaneously altering the frequencies of the primary frequency
20 signals, and inducing a time delay across the electrodes in the
21 delay-steered direction 13.

22 There is now described in more detail the derivation of the
23 electrode pattern of piezoelectric elements. First, there is
24 chosen a first primary frequency, f_1 , and corresponding beam

1 direction, theta, to be generated by the monolithic active
2 surface 1. Next, there is calculated the (one dimensional)
3 velocity distribution over the surface required to generate the
4 desired beam. This can be accomplished by specifying the far
5 field beam pattern desired and performing an inverse Fast
6 Fourier Transform (FFT) to generate the required distribution.

7 As used herein, "far field beam pattern" refers to the
8 distribution of acoustic energy at a large distance away from
9 the acoustic source that produces it. Normally it refers to how
10 focused the acoustic energy is in one direction.

11 Next, a separation distance 37 is computed for each primary
12 frequency row. Separation distance 37 is the distance required
13 between each similar piezoelectric element 19,21,23,25 located
14 in real or imaginary frequency row 27,29. For example, note
15 that in FIG. 2 separation distance 37 is the distance between
16 each R+ piezoelectric element 19.

17 As discussed above, the separation distance 37 is computed
18 from the desired primary frequency f_1 and steering angle theta.
19 First, Given a desired frequency F and steering angle q, compute
20 $F \sin q$. This has the dimensions of frequency and the
21 corresponding wavelength on the surface is $\lambda=c/(F \sin q)$. By
22 making a repeating electrode pattern on the surface with this
23 wavelength, any other frequency f_1 will steer to a different
24 angle theta according to $F \sin q = f_1 \sin(\theta)$.

1 As an example, for a primary of F=240 kHz and a desired
2 steer angle of 30 degrees, $F \sin q = 240K (0.5) = 120K$. Since the
3 speed of sound in water is about 60000 inches/sec,
4 $l = 60000/120000 = 0.5$ inches. This is the repeat pattern required
5 of the corresponding electrode for this frequency and steer
6 angle.

7 Generate a pattern on the surface of the active material
8 that represents the desired complex surface velocity at any
9 offset x_0 along the frequency-steered direction 11 such that
10 $V(x) = V_r(x) + V_i(x)$. At any given frequency, the real and imaginary
11 components of the complex velocity, V_r and V_i , can be realized by
12 driving two piezoelectric elements 19, 21, 23, 25 (one real and one
13 imaginary) of the surface, say at x_0 , with signals that are 90°
14 out of phase. Further, a positive or negative V_r is implemented
15 (at R+ piezoelectric elements 19 and R- piezoelectric elements
16 21 respectively) by driving at phase 0° or 180° and a positive
17 or negative V_i is implemented by driving at 90° or 270° (at I+
18 piezoelectric elements 25 and I- piezoelectric elements 23
19 respectively).

20 As discussed above, the result is that any slice 4 of the
21 surface (say at offset x_0 , as shown in FIG. 2) along the
22 frequency steered direction 11 can be driven with a complex
23 voltage $V_r(x_0) + V_i(x_0)$ by doing the following. First, define a
24 single separation distance 37 between each corresponding

1 piezoelectric element 19,21,25, and 23 as discussed above to
2 generate a constant spacing between the piezoelectric elements
3 19,21,25, and 23 arranged in alternating fashion as illustrated
4 in FIG. 2. Next, move slice 4 along primary frequency row 15
5 altering the extent of the portion of each repeating real
6 piezoelectric element 19,21 intersecting slice 4 such that such
7 portions are proportional to $V_r(x_0)$ and connect each similar real
8 piezoelectric element 19,21 to the appropriate voltage source
9 (0 to 180° phase if V_r has a + or - sign). Next, do the same for
10 each repeating imaginary piezoelectric element 25,23 altering
11 the extent of the portion of each repeating imaginary
12 piezoelectric element 25,23 intersecting slice 4 such that such
13 portions are proportional to $V_i(x_0)$ and connect each similar
14 imaginary piezoelectric element 25,23 to the appropriate
15 voltage source (90 or 270° phase if V_i has a + or - sign). As
16 the offset, x , changes, the portion of each repeating
17 piezoelectric element 19,21,23,25 intersecting slice 4 changes,
18 due to the change in complex velocity along the frequency
19 steering direction 11, giving rise to the pattern in FIG. 2.

20 The same process described above is repeated for the second
21 primary frequency, f_2 , and direction theta. In a preferred
22 embodiment, F is chosen to be approximately 260kHz. F_1 and f_2
23 are typically chosen to be approximately $F \pm 20$ kHz or 240kHz and
24 280kHz respectively. This results in a difference frequency of

1 40kHz. However, the present invention is drawn broadly to
2 include any F, f_1 , and f_2 sufficient to operate in a desired
3 parametric mode.

4 The filigree array of the present invention requires only N
5 independent control points in the delay steered direction and
6 four phase-delayed copies (0, 90, 180, 270 degrees) of each
7 primary frequency signal for each primary frequency row 15,17.
8 As there are two primary frequency rows 15,17, the result is 8N
9 control points for a single coupled frequency pair 41. While
10 there are a plurality of coupled frequency pairs 41 stacked in
11 delayed steered direction each with a means for receiving time
12 delayed copies of the two primary frequency signals, such delays
13 can be implemented as described above using conventional and
14 cost effective time delay circuitry and apparatus.

15 Use of the parametric mode sound generation simultaneously
16 achieves low frequency performance and high directionality using
17 relatively small size apertures. In many applications low
18 frequency is of interest because of low attenuation, and other
19 target characteristics. Conventional (linear mode) low
20 frequency sources require very large radiating apertures to form
21 directional acoustic beams.

22 In summary, this invention provides the capability to form
23 highly directional (<5 degrees) acoustic beams that remain

1 relatively constant over a broad range of frequency (~2 octaves)
2 using relatively small radiating apertures (~6 to 12 inches).

3 Several underwater sonar applications exist for steered
4 directional acoustic beams including, but not limited to, mine
5 detection, acoustic communication (ACOMMS), and surface
6 scanning. In the present disclosed approach, the number of
7 active control elements needed to form a steered directional
8 acoustic beam is much lower than that required to conventional
9 broadband time-delay beam forming. Therefore this invention
10 simplifies electronics.

11 It is apparent that there has been provided in accordance
12 with the present invention a transducer for steering parametric
13 acoustic beams which fully satisfies the objects, means, and
14 advantages set forth previously herein. While the present
15 invention has been described in the context of specific
16 embodiments thereof, other alternatives, modifications, and
17 variations will become apparent to those skilled in the art
18 having read the foregoing description. Accordingly, it is
19 intended to embrace those alternatives, modifications, and
20 variations as fall within the broad scope of the appended
21 claims.

1 Attorney Docket No. 83154

2

3 FILIGREE ELECTRODE PATTERN APPARATUS FOR
4 STEERING PARAMETRIC MODE ACOUSTIC BEAMS

5

6 ABSTRACT OF THE DISCLOSURE

7 A piezoelectric embedded monolithic active surface for
8 transmitting a directed acoustic beam comprising a monolithic
9 active surface, a plurality of piezoelectric elements embedded
10 on the surface forming an array comprising, a plurality of
11 coupled frequency pairs comprising, a first primary frequency
12 row extending in a frequency steered direction the first primary
13 frequency row enabled to accept a first primary frequency
14 signal, and a second primary frequency row extending in the
15 frequency steered direction and located adjacent to the first
16 primary frequency row the second primary frequency row enabled
17 to accept a second primary frequency signal, wherein the
18 plurality of coupled frequency pairs repeat in a delay-steered
19 direction and wherein each of the coupled frequency pairs are
20 enabled to accept a time delayed copy of the first and second
21 primary frequency signals.

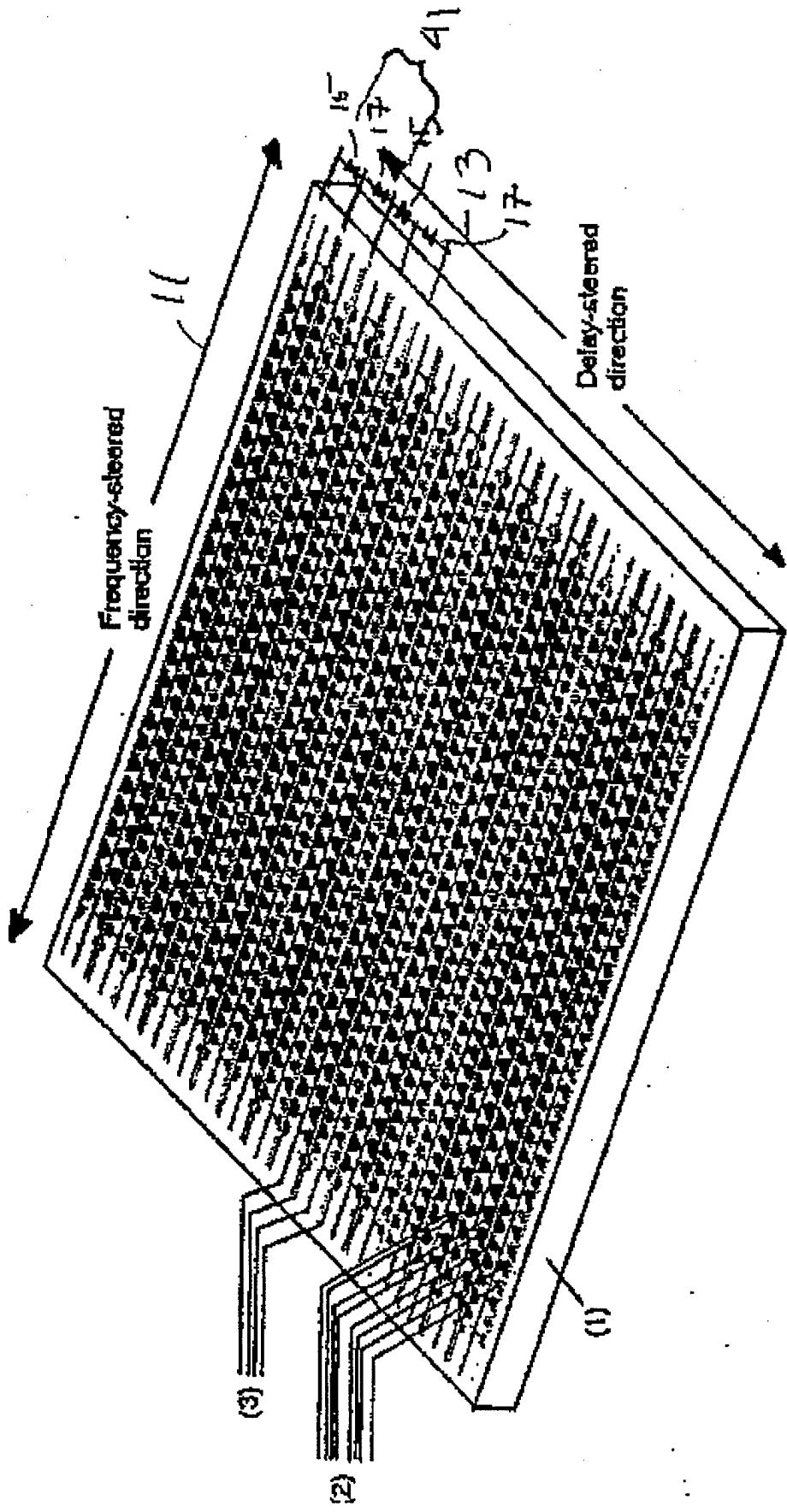
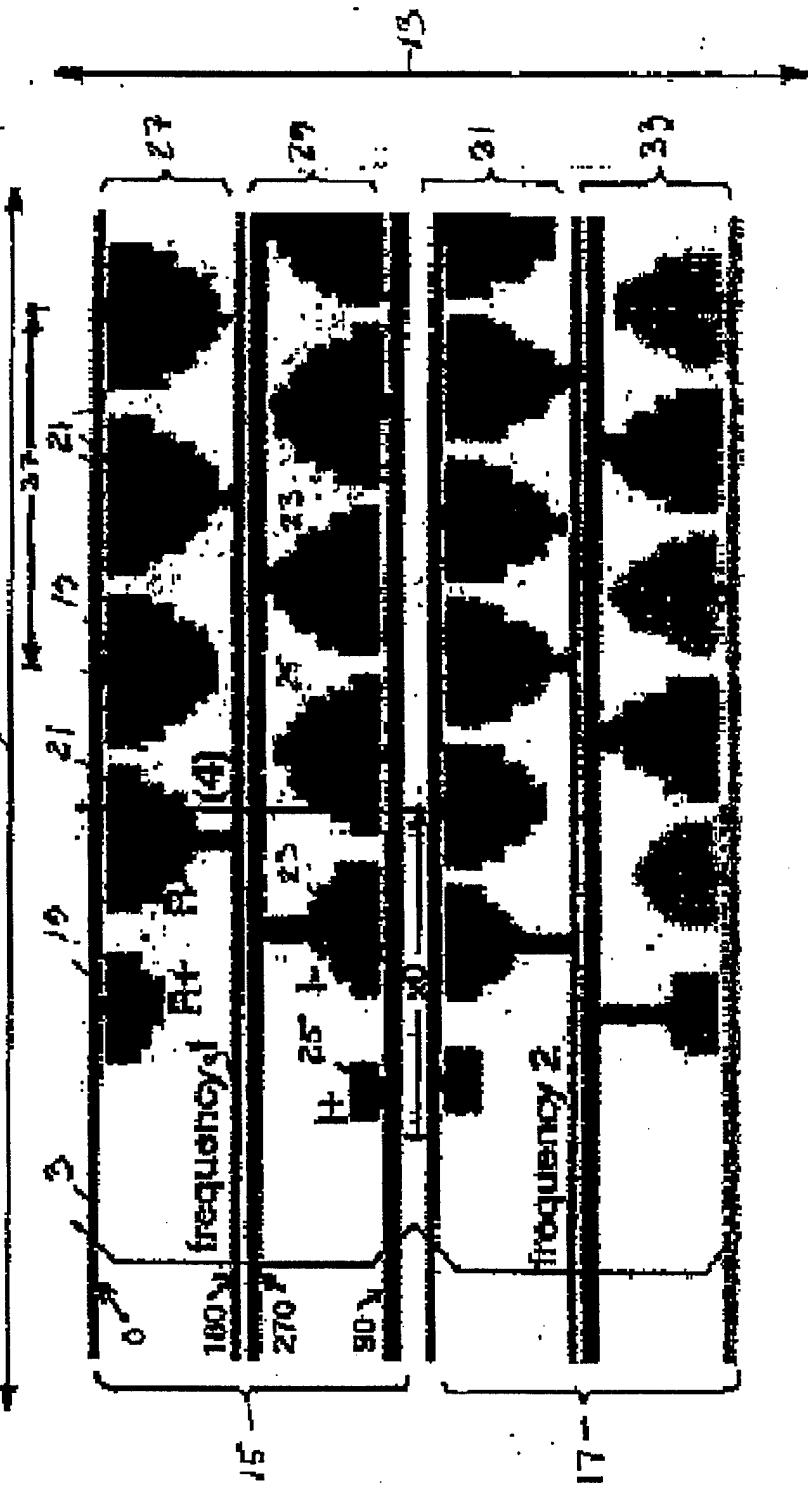


Figure 1

Fig. 2



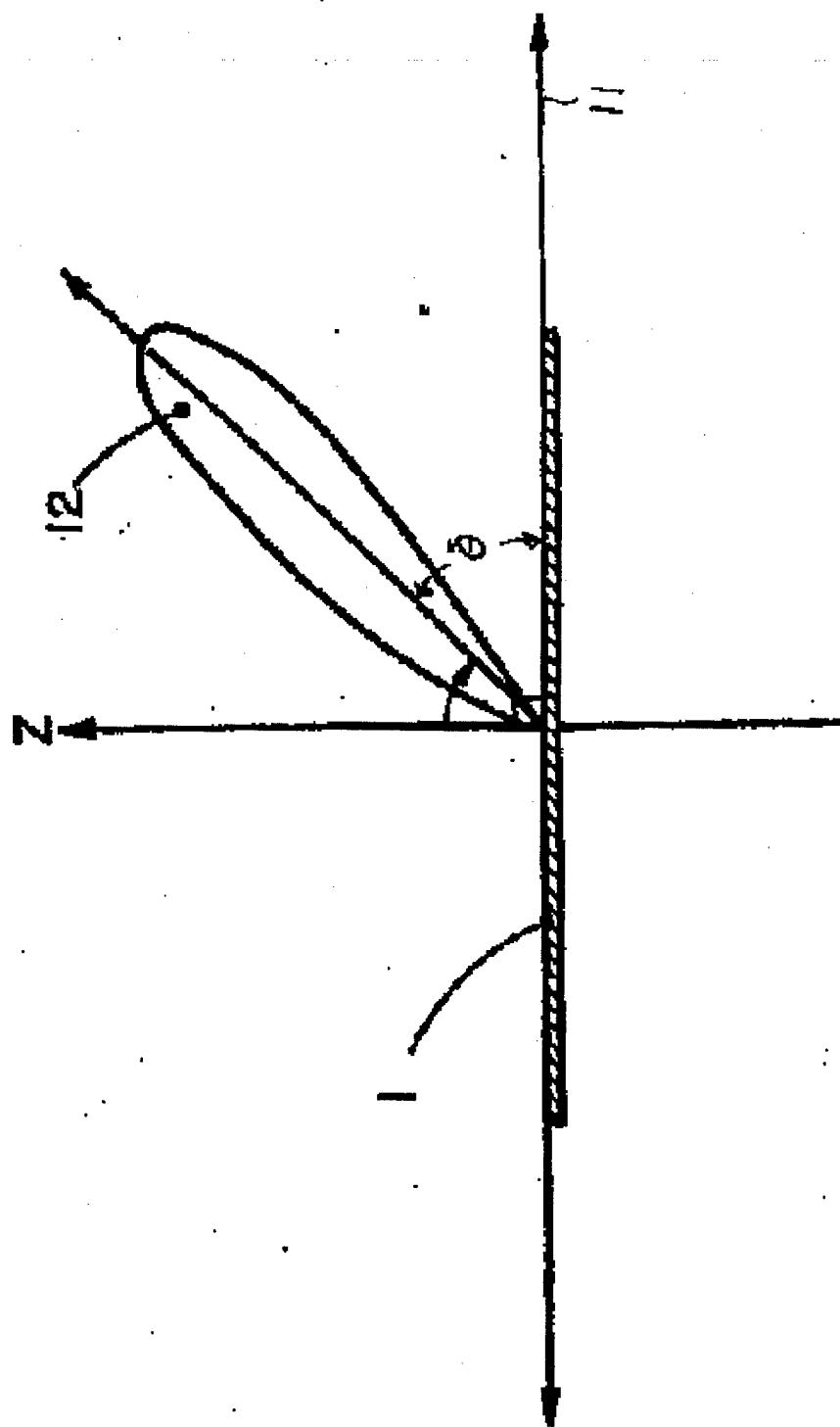


Fig. 3